5
Attention and Performance Limitations

INTRODUCTION

As Pashler (1998, p. 1) pointed out, "Attention has long posed a major challenge for psychologists." Historically, the concept of "attention" was treated as important by many philosophers and psychologists in the late 19th century. However, it fell into disrepute, because the behaviourists regarded all internal processes with the utmost suspicion. Attention became fashionable again following the publication of Broadbent's book *Perception and Communication* in 1958, and has remained an important topic ever since.

Attention is most commonly used to refer to selectivity of processing. This was the sense emphasised by William James (1890, pp. 403–404):

> Everyone knows what attention is. It is the taking possession of the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalisation, concentration, of consciousness are of its essence.

What is the relationship between attention and consciousness? Baars (1997) argued that access to consciousness is controlled by attentional mechanisms. Consider, for example, sentences such as, "We look in order to see" or "We listen in order to hear". According to Baars (1997, p. 364), "The distinction is between selecting an experience and being conscious of the selected event. In everyday language, the first word of each pair ["look"; "listen"] involves attention; the second word ["see"; "hear"] involves consciousness." In other words, attention resembles choosing a television channel and consciousness resembles the picture on the screen.

William James (1890) distinguished between "active" and "passive" modes of attention. Attention is active when controlled in a top-down way by the individual's goals, whereas it is passive when controlled in a bottom-up way by external stimuli (e.g., a loud noise). According to Yantis (1998, p. 252), "Stimulus-driven attentional control is both faster and more potent than goal-driven attentional control." The reason is that it typically requires processing effort to decide which stimulus is most relevant to the current goal.

We have implied that there is a unitary attentional system. However, this is improbable. As Allport (1993, pp. 203–204) pointed out:

> It seems no more plausible that there should be one unique mechanism, or computational resource, as the causal basis of all attentional phenomena than that there should be a unitary causal basis of thought, or perception, or of any other traditional category of folk psychology…Reference to attention (or to
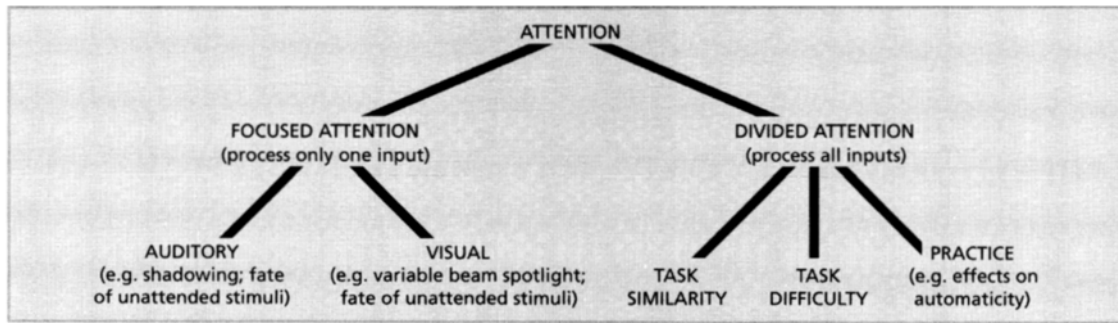
FIGURE 5.1

The ways in which different topics in attention are related to each other.

the central executive, or even to the anterior attention system) as an unspecified causal mechanism explains nothing.

There is a crucial distinction between focused and divided attention (see Figure 5.1). *Focused attention* is studied by presenting people with two or more stimulus inputs at the same time, and instructing them respond to only one. Work on focused attention can tell us how effectively people select certain inputs rather than others, and it enables us to study the nature of the selection process and the fate of unattended stimuli. *Divided attention* is also studied by presenting at least two stimulus inputs at the same time, but with instructions that *all* stimulus inputs must be attended to and responded to. Studies of divided attention provide useful information about an individual's processing limitations, and may tell us something about attentional mechanisms and their capacity.

The distinction between focused and divided attention can be related to some of the distinctions discussed earlier. Individuals typically *decide* whether to engage in focused or divided attention. Thus, the use of focused or divided attention is often determined by goal-driven or top-down attentional control processes.

There are *three* important limitations of attentional research. First, although we can attend to either the external environment or the internal environment (i.e., our own thoughts and information in long-term memory), most research has been concerned only with the former. Why is this? Researchers can identify and control environmental stimuli in ways that are impossible with internal determinants of attention.

Second, what we attend to in the real world is largely determined by our current goals. As Allport (1989, p. 664) pointed out, "What is important to recognise…is not the location of some imaginary boundary between the provinces of attention and motivation but, to the contrary, their essential interdependence." In most research, on the other hand, what participants attend to is determined by the experimental instructions rather than by their motivational states.

Third, as Tipper, Lortie, and Baylis (1992) noted, in the real world we generally attend to three-dimensional people and objects, and decide what actions might be suitable with respect to them. In the laboratory, the emphasis is on "experiments that briefly present static 2D displays and require arbitrary responses. It is clear that such experimental situations are rarely encountered in our usual interactions with the environment" (Tipper et al., 1992, p. 902).

FOCUSED AUDITORY ATTENTION

The British scientist Colin Cherry was working in an electronics research laboratory at the Massachusetts Institute of Technology, but became involved in psychological research. What fascinated Cherry was the "cocktail party" problem: how are we able to follow just one conversation when several people are all talking at once? Cherry (1953) found that this ability involves using physical differences (e.g., sex of speaker; voice intensity; speaker location) to maintain attention to a chosen auditory message. When Cherry presented two messages in the same voice to both ears at once (thereby eliminating these physical differences), listeners found it very hard to separate out the two messages on the basis of meaning alone.

Cherry also carried out studies in which one auditory message had to be shadowed (i.e., repeated back out loud) while a second auditory message was played to the other ear. Very little information seemed to be extracted from the second or non-attended message. Listeners seldom noticed when that message was spoken in a foreign language or in reversed speech. In contrast, physical changes (e.g., a pure tone) were nearly always detected. The conclusion that unattended auditory information receives practically no processing was supported by other evidence. For example, there was very little memory for unattended words even when they were presented 35 times each (Moray, 1959).

Broadbent's theory

Broadbent (1958) felt the findings from the shadowing task were important. He was also impressed by data from a memory task in which three pairs of digits were presented dichotically, i.e., three digits were heard one after the other by one ear, at the same time as three different digits were presented to the other ear. Most participants chose to recall the digits ear by ear rather than pair by pair. Thus, if 496 were presented to one ear and 852 to the other ear, recall would be 496852 rather than 489562.

Broadbent (1958) accounted for the various findings as follows (see Figure 5.2):

- Two stimuli or messages presented at the same time gain access in parallel (at the same time) to a sensory buffer.
- One of the inputs is then allowed through a filter on the basis of its physical characteristics, with the other input remaining in the buffer for later processing.
- This filter prevents overloading of the limited-capacity mechanism beyond the filter; this mechanism processes the input thoroughly (e.g., in terms of its meaning).

This theory handles Cherry's basic findings, with unattended messages being rejected by the filter and thus receiving minimal processing. It also accounts for performance on Broadbent's dichotic task, because the filter selects one input on the basis of the most prominent physical characteristic distinguishing the two inputs

(i.e., the ear of arrival). However, it is assumed incorrectly that the unattended message is always rejected at an early stage of processing. The original shadowing experiments used participants with very little experience of shadowing messages, so nearly all their available processing resources had to be allocated to shadowing. Underwood (1974) asked participants to detect digits presented on either the shadowed or the non-shadowed message. Naive participants detected only 8% of the digits on the non-shadowed message, but an experienced researcher in the area (Neville Moray) detected 67% of them.

In most of the early work on the shadowing task, the two messages were rather similar (i.e., they were both auditorily presented verbal messages). Allport, Antonis, and Reynolds (1972) found the degree of *similarity* between the two messages had a major impact on memory for the non-shadowed message. When shadowing of auditorily presented passages was combined with auditory presentation of words, memory for the words was very poor. However, when shadowing was combined with picture presentation, memory for the pictures was very good (90% correct). If two inputs are dissimilar, they can both be processed more fully than was allowed for on Broadbent's filter theory.

In the early studies, it was concluded that there was no processing of the meaning of unattended messages because the participants had no conscious awareness of their meaning. However, meaning may be processed without awareness. Von Wright, Anderson, and Stenman (1975) presented two lists of words auditorily, with instructions to shadow one list and ignore the other. When a word that had previously been associated with electric shock was presented on the non-attended list, there was sometimes a physiological reaction (galvanic skin response). The same effect was produced by presenting a word very similar in sound or meaning to the shocked word. Thus, information on the unattended message was sometimes processed for sound and meaning, even though the participants were not consciously aware that a word related to the previously shocked word had been presented.

Evaluation

Broadbent's (1958) proposed an *inflexible* system of selective attention that cannot account for the great variability in the amount of analysis of the non-shadowed message. The same inflexibility of the filter theory is shown in its assumption that the filter selects information on the basis of physical features. This assumption is supported by the tendency of participants to recall dichotically presented digits ear by ear. However, Gray and Wedderburn (1960) made use of a version of the dichotic task in which "Who 6 there" might be presented to one ear as "4 goes 1" was presented to the other ear. The preferred order of report was determined by meaning (e.g., "who goes there" followed by "4 6 1"). The fact that selection can be based on the meaning of presented information is inconsistent with filter theory.

Alternative theories

Treisman (1960) found with the shadowing task that the participants sometimes said a word that had been presented on the unattended channel. This is known as "breakthrough", and typically occurs when the word on the unattended channel is highly probable in the context of the message on the attended channel. Even in those circumstances, however, Treisman (1960) only observed breakthrough on 6% of trials.

Findings such as those of Treisman (1960) led Treisman (1964) to propose a theory in which the filter reduces or attenuates the analysis of unattended information (see Figure 5.2). Whereas Broadbent had suggested that there was a bottle-neck early in processing, Treisman claimed that the location of the bottleneck was more flexible. She proposed that stimulus analysis proceeds systematically through a hierarchy starting with analyses based on physical cues, syllabic pattern, and specific words, and moving on
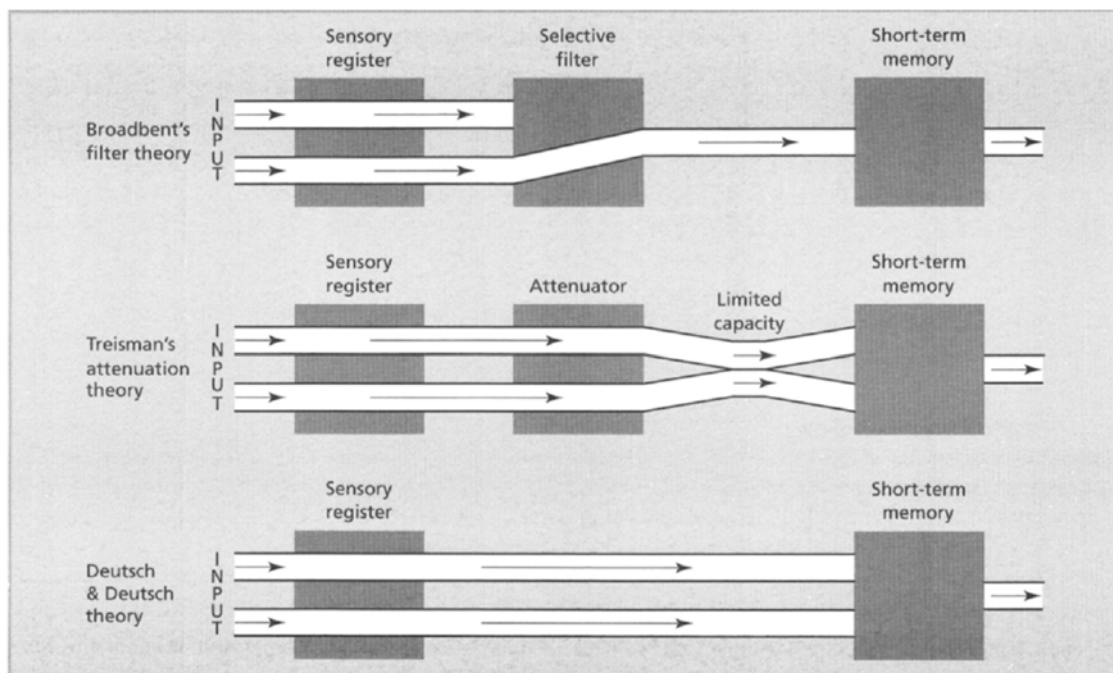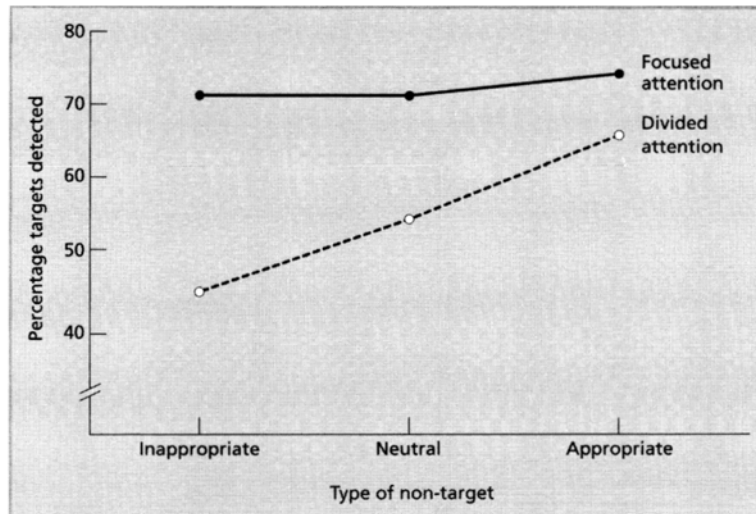
FIGURE 5.2

A comparison of Broadbent's theory (top); Treisman's theory (middle); and Deutsch and Deutsch's theory (bottom).

to analyses based on individual words, grammatical structure, and meaning. If there is insufficient processing capacity to permit full stimulus analysis, then tests towards the top of the hierarchy are omitted.

Another important aspect of the theory proposed by Treisman (1964) was that the thresholds of all stimuli (e.g., words) consistent with current expectations are lowered. As a result, partially processed stimuli on the unattended channel sometimes exceed the threshold of conscious awareness. This aspect of the theory helps to account for the phenomenon of breakthrough.

Treisman's theory accounted for the extensive processing of unattended sources of information that had proved embarrassing for Broadbent. However, the same facts were also explained by Deutsch and Deutsch (1963). They argued that all stimuli are fully analysed, with the most important or relevant stimulus determining the response (see Figure 5.2). This theory places the bottleneck in processing much nearer the response end of the processing system than did Treisman's attenuation theory. As a result, the theory proposed by Deutsch and Deutsch (1963) is often called late-selection theory, whereas the theories of Broadbent (1958) and Treisman (1964) are termed early-selection theories.

Treisman and Geffen (1967) had participants shadow one of two auditory messages, and tap when they detected a target word in either message. According to Treisman's theory, there should be attenuated analysis of the non-shadowed message, and so fewer targets should be detected on that message. According to Deutsch and Deutsch, there is complete perceptual analysis of all stimuli, and so there should be no difference in detection rates between the two messages. In fact, detection rates were much higher on the shadowed than the non-shadowed message (87% vs. 8%, respectively).

FIGURE 5.3

Effects of attention condition (divided vs. focused) and of type of non-target on target detection. Data from Johnston and Wilson (1980).

According to Deutsch and Deutsch (1967), only important inputs lead to responses. As the task used by Treisman and Geffen (1967) required their participants to make two responses (i.e., shadow and tap) to target words in the shadowed message, but only one response (i.e., tap) to targets in the non-shadowed message, the shadowed targets were more important than the non-shadowed ones.

Treisman and Riley (1969) responded by carrying out a study in which exactly the same response was made to all targets. Participants stopped shadowing and tapped when they detected a target in either message. Many more target words were detected on the shadowed message than the non-shadowed one.

Neurophysiological studies provide support for early-selection theories (see Luck, 1998, for a review). Woldorff et al. (1993) used the task of detecting auditory targets presented to the attended ear, with fast trains of non-targets being presented to each ear. Event-related potentials (ERPs; see Chapter 1) were recorded from attended and unattended stimuli. There were greater ERPs to attended stimuli 20–50 milliseconds after stimulus onset. Thus, there is more processing of attended than unattended auditory stimuli starting from the initial activation of the auditory cortex.

Johnston and Heinz's theory

Johnston and Heinz (1978) proposed a flexible model of attention incorporating the following assumptions:

- The more stages of processing that take place prior to selection, the greater the demands on processing capacity.
- Selection occurs as early in processing as possible to minimise demands on capacity.

Johnston and Wilson (1980) tested these assumptions. Pairs of words were presented together dichotically (i.e., one word to each ear), and the task was to identify target words consisting of members of a designated

category. The targets were ambiguous words having two distinct meanings. If the category was "articles of clothing", then "socks" would be a possible target word. Each target word was accompanied by a non-target word biasing the appropriate meaning of the target (e.g., "smelly"), or a non-target word biasing the inappropriate meaning (e.g., "punches"), or by a neutral non-target word (e.g., "Tuesday").

When participants did not know which ear targets would arrive at (divided attention), appropriate non-targets facilitated the detection of targets and inappropriate non-targets impaired performance (see Figure 5.3). Thus, when attention had to be divided, the non-target words were processed for meaning. When participants knew all the targets would be presented to the left ear, the type of non-target word had no effect on target detection. Thus, non-targets were not processed for meaning in this focused attention condition, and so the amount of processing received by non-target stimuli is only as much as is necessary for task performance.

Section summary

The analysis of unattended auditory inputs can be greater than was originally thought. However, the full analysis theory of Deutsch and Deutsch (1963) seems dubious. The most reasonable account of focused auditory attention may be along the lines suggested by Treisman (1964), with reduced or attenuated processing of sources of information outside focal attention. The extent of such processing is probably flexible, being determined in part by task demands (Johnston & Heinz, 1978). Styles (1997, p. 28) made a telling point: "Discovering precisely where selection occurs is only one small part of the issues surrounding attention, and finding *where* selection takes place may not help us to understand *why* or *how* this happens.

FOCUSED VISUAL ATTENTION

Over the past 25 years, most researchers have studied visual rather than auditory attention. Why is this? Probably the main reason is that it is generally easier to control the presentation times of visual stimuli than of auditory stimuli.

Some of the issues we will be discussing in this section of the chapter have been considered from the cognitive neuropsychological perspective. Three attentional disorders have been studied fairly thoroughly: neglect; extinction; and Balint's syndrome (see Driver, 1998, for a review). *Neglect* is typically found after brain damage in the right parietal lobe, and is often the result of a stroke. Neglect patients with right-hemisphere damage do not notice, or fail to respond to, objects presented to their left (or contralesional) side. For example, when neglect patients draw an object or copy a drawing, they typically leave out everything on the left side of it. According to Driver (1998, p. 308), "The essential problem in neglect may be that while the patient can, in principle, look or attend toward the contralesional side, they usually fail to do so spontaneously." In addition, neglect patients can also show neglect on tasks involving images rather than visual perception (Bisiach & Luzzati, 1978). It is important to note that "neglect is not a single disorder but a range of disorders which can occur in varying degrees within any patient" (Parkin, 1996, p. 91).

It might be thought that neglect occurs because stimuli on one side of the visual field are not processed perceptually. However, most of the evidence indicates that that is not typically the case. For example, Marshall and Halligan (1988) presented a neglect patient with two drawings of a house that were identical, except that the house presented to the left visual field had flames coming out of one of its windows. The patient was unable to report any differences between the two drawings, but indicated that she would prefer to live in the house on the right.

How can we explain neglect? According to Parkin (1996, p. 108), "At the moment the most convincing class of theories concerning neglect are those that propose some form of attentional deficit. Essentially these theories suggest that there is an imbalance in the amount of attention allocated to left and right…However, the idea that a single theory of neglect will emerge is highly unlikely because of the diversity of defects being discovered." Posner's attentional theory of neglect is discussed later.

Extinction is a phenomenon frequently found in neglect patients. A *single* stimulus on either side of the visual field can be judged normally. However, when *two* stimuli are presented together, the one farther towards the side of the visual field away from the damage tends to go undetected. Some patients only show extinction when the two objects presented simultaneously are the same.

Balint's syndrome is associated with lesions in both hemispheres involving the posterior parietal lobe or parieto-occipital junction. It is characterised by various attentional problems. These include fixed gazing, gross misreaching for objects, and *simultanagnosia,* in which only one object can be attended to at a time. As Martin (1998, p. 228) noted, "A patient with Balint's syndrome might focus quite narrowly on the tip of a cigarette in his or her mouth and be unable to see a match offered a short distance away."

Convincing evidence that Balint's patients can only attend to one object at a time was reported by Humphreys and Riddoch (1993). When Balint's patients were presented with a mixture of red and green circles, they were generally unable to report seeing both colours. Presumably this happened because the patients could only attend to a single circle at a time. However, when the red and green circles were joined by lines (so that each object contained red and green), the patients' performance was much better.

Spotlight or zoom lens?

According to Pashler (1998, p. 4), "the findings with visual stimuli have closely paralleled those with auditory stimuli". This similarity is clear when we consider research on focused attention. In some ways, focused visual attention resembles a spotlight. Everything within a fairly small region of the visual field can be seen clearly, but it is much harder to see anything not falling within the beam of the attentional spotlight. Attention can be shifted by moving the spotlight, and the simplest assumption is that the attentional spotlight moves at a constant rate (see Yantis, 1998). A more complex view of focused visual attention was put forward by Eriksen and St. James (1986). According to their zoom-lens model, attention is directed to a given region of the visual field. However, the area of focal attention can be increased or decreased in line with task demands.

Posner (1980) favoured the spotlight notion. He argued that there can be *covert attention,* in which the attentional spotlight shifts to a different spatial location in the absence of an eye movement. In his studies, the participants responded as rapidly as possible when they detected the onset of a light. Shortly before the onset of the light, they were presented with a central cue (arrow pointing to the left or right) or a peripheral cue (brief illumination of a box outline). These cues were mostly valid (i.e., they indicated where the target light would appear), but sometimes they were invalid (i.e., they provided misleading information about the location of the target light).

Posner's (1980) key findings were that valid cues produced faster responding to light onset than did neutral cues (a central cross), whereas invalid cues produced slower responding than neutral cues. The findings were comparable for central and peripheral cues, and were obtained in the absence of eye movements. When the cues were valid on only a small fraction of trials, they were ignored when they were central cues but affected performance when they were peripheral cues. These findings led Posner (1980) to distinguish between two systems:
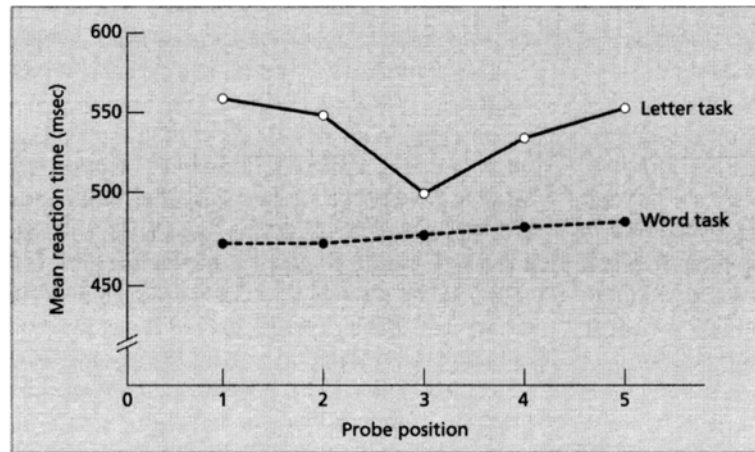
FIGURE 5.4

Mean reaction time to the probe as a function of probe position. The probe was presented at the time that a letter string would have been presented. Data from LaBerge (1983).

1. An endogenous system, which is controlled by the participant's intentions and is involved when central cues are presented.
2. An exogenous system, which automatically shifts attention and is involved when peripheral cues are presented.

Some evidence does not support the spotlight notion. Kwak, Dagenbach, and Egeth (1991) presented their participants with two letters at a time, and asked them to decide whether they were the same. The decision times were the same whether the letters were close together or far apart. This is inconsistent with the notion that visual attention is like a spotlight moving at a given rate.

Evidence in favour of the zoom-lens model was reported by LaBerge (1983). Five-letter words were presented. A probe requiring rapid response was occasionally presented instead of, or immediately after, the word. The probe could appear in the spatial position of any of the five letters of the word. In one condition, an attempt was made to focus the participants' attention on the middle letter of the five-letter word by asking them to categorise that letter. In another condition, the participants were required to categorise the entire word. It was expected that this would lead the participants to adopt a broader attentional beam.

The findings on speed of detection of the probe are shown in Figure 5.4. LaBerge (1983) assumed that the probe was responded to faster when it fell within the central attentional beam than when it did not. On this assumption, the attentional spotlight can have either a very narrow (letter task) or rather broad (word task) beam.

Eriksen and St. James (1986) also obtained support for the zoom-lens model. Their participants performed a task on a target stimulus whose location was indicated beforehand. Performance was impaired by the presence of distracting visual stimuli. However, the area over which interference effects were found was less when the participants had longer forewarning of the target stimulus. Presumably visual attention zoomed in more precisely on the area around the target stimulus over time.

Evaluation

As the zoom-lens model predicts, the size of the visual field within focal attention can vary substantially. However, focused visual attention is more complex than is implied by the model. For example, consider a study by Juola, Bowhuis, Cooper, and Warner (1991). A target letter (L or R) which had to be identified was presented in one of three rings having the same centre: an inner, a middle, and an outer ring. The participants fixated the centre of the display, and were given a cue that mostly provided accurate information as to the ring in which the target would be presented. If visual attention is like a spotlight or zoom lens, speed and accuracy of performance would be greatest for targets presented in the inner ring. In fact, performance was best when the target appeared in the ring that had been cued. This suggests that visual attention can be allocated in an O-shaped pattern to include only the outer or the middle ring.

There is a more fundamental objection to the spotlight and zoom-lens models. It is assumed within both models that visual attention is directed towards a given region in the visual field. However, visual attention is often directed to *objects* rather than to a particular *region*. Consider, for example, a study by Neisser and Becklen (1975). They superimposed two moving scenes on top of each other. Their participants could easily attend to one scene while ignoring the other. These findings suggest that objects within the visual environment can be the main focus of attention.

According to the spotlight approach, it might be expected that visual attention in patients with neglect and extinction would be limited only in area. However, this is not so. Marshall and Halligan (1994) presented a patient with neglect in the left visual field with ambiguous displays, each of which could be seen as a black shape against a white background or as a white shape on a black background. There was a jagged edge dividing the two shapes at the centre of each display. The patient was able to copy this jagged edge when asked to draw the shape on the left side of the display, but could not copy exactly the same edge when asked to draw the shape on the right side. Thus, the patient attended to objects rather than simply to a region of visual space.

Ward, Goodrich, and Driver (1994) studied two patients with extinction in the left visual field. Two stimuli were presented at once, and they either formed a good perceptual group (e.g., "[and]") or they did not (e.g., "[and o"). The patients were much better at detecting the stimuli on the left side of the visual field when they belonged to a good perceptual group. Thus, visual attention in extinction patients is affected by grouping factors as well as by location.

What conclusion can we draw from studies such as those of Marshall and Halligan (1994) and Ward et al. (1994)? According to Driver (1998, p. 315), "The spatial extent of both normal and pathological [abnormal or diseased] attention is substantially modulated by grouping processes. Clearly, human covert attention is rather more sophisticated than a simple 'spotlight' metaphor implies."

Unattended visual stimuli

There is generally rather limited processing of unattended auditory stimuli. What happens to unattended visual stimuli? Neurophysiological evidence suggests there is reduced processing of such stimuli. Luck (1998) discussed several studies in which the participants fixated a central point while attending to the left or the right visual field. A rapid succession of bars was presented to both fields, and the task involved detecting targets (smaller bars) in the attended visual field. Event-related potentials (ERPs; see Chapter 1) are larger to attended than to unattended stimuli. The ERPs to the two types of stimuli begin to differ with the first positive wave (P1), which starts about 75 milliseconds after stimulus onset.

Heinze et al. (1994) used a similar procedure to the one just described, and obtained PET scans as well as ERPs. They replicated the greater P1 to attended than to unattended visual stimuli. However, according to Luck (1998, p. 274), their key finding was that, "visual attention influences sensory processing in

extrastriate visual cortex within 100 ms of stimulus onset, consistent with early-selection models of attention."

Evidence suggesting that there is very little processing of unattended visual stimuli was reported by Francolini and Egeth (1980). Circular arrays of red and black letters or numerals were presented, and the task was to count the number of red items and to ignore the black items. Performance speed was reduced when the *red* items consisted of numerals conflicting with the answer, but there was no interference effect from the *black* items. These findings suggest there was little or no processing of the to-be-ignored black items.

The findings of Driver and Tipper (1989) contradicted this conclusion. They used the same task as Francolini and Egeth (1980), but focused on whether conflicting numerical values had been presented on the *previous* trial. There was an interference effect, and it was of the same size from red and black items. The finding that performance on any given trials was affected by the numerical values of to-be-ignored items from the previous trial means those items must have been processed. This is the phenomenon of *negative priming*. In this phenomenon, the processing of a target stimulus is inhibited if that stimulus or one very similar to it was an unattended or distracting stimulus on the previous trial.

Further evidence that there is often more processing of unattended visual stimuli than initially seems to be the case has been reported with neglect patients. McGlinchey-Berroth et al. (1993) asked such patients to decide which of two drawings matched a drawing presented immediately beforehand to the left or the right visual field. Neglect patients performed well when the initial drawing was presented to the right visual field, but at chance level when it was presented to the left visual field (see Figure 5.5). The latter finding suggests that stimuli in the left visual field were not processed. However, a very different conclusion emerged from a second study, in which neglect patients had to decide whether letter strings formed words. Decision times were faster on "yes" trials when the letter string was preceded by a semantically related object rather than an unrelated object. This effect was the same size regardless of whether the object was presented to the left or the right visual field (see Figure 5.5), indicating that there is some processing of left-field stimuli by neglect patients.

Section summary

Neurophysiological evidence suggests there is reduced processing of unattended visual stimuli. The fact that processing of, and responding to, attended visual stimuli is often unaffected by unattended stimuli suggests there is very little processing of such stimuli. However, when sensitive measures are used, there is strong evidence for some processing of the meaning of unattended stimuli by normals and by neglect patients. For example, normals exhibit a phenomenon known as negative priming.

Visual search

One of the main ways we use focused visual attention in our everyday lives is in visual search (see Chapter 3). For example, we search through the books in a library looking for the one we want, or we look for a friend in a crowded room. An attempt to study the processes involved has been made by using visual search tasks. The participants are presented with a visual display containing a variable number of items (the set or display size). A target (e.g., red G) is presented on half the trials, and the task is to decide as rapidly as possible whether the target is present in the display. Theory and research on this task are discussed next.

Feature integration theory
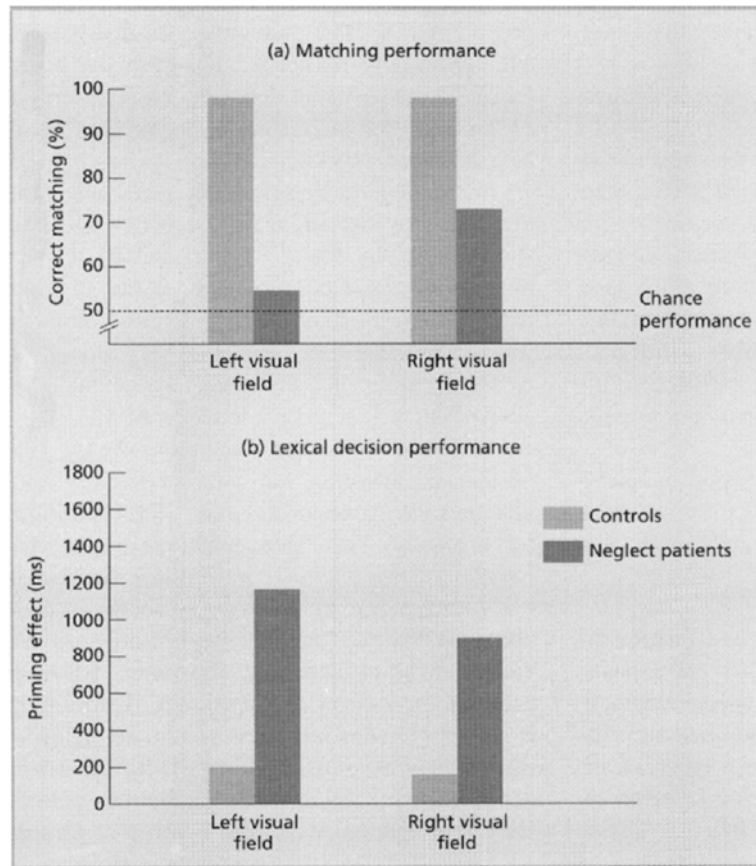
FIGURE 5.5

Effects of prior presentation of a drawing to the left or right visual field on matching performance and lexical decision in neglect patients. Data from McGlinchey-Berroth et al. (1993).

The most influential approach to visual search is the feature integration theory put forward by Treisman (eg., 1988, 1992). She drew a distinction between the features of objects (e.g., colour, size, lines of particular orientation) and the objects themselves. Her theory based on this distinction includes the following assumptions:

- There is a rapid initial parallel process in which the visual features of objects in the environment are processed together; this is not dependent on attention.
- There is then a serial process in which features are combined to form objects.
- The serial process is slower than the initial parallel process, especially when the set size is large.
- Features can be combined by focused attending to the location of the object, in which case focused attention provides the "glue" forming unitary objects from the available features.
- Feature combination can be influenced by stored knowledge (e.g., bananas are usually yellow).
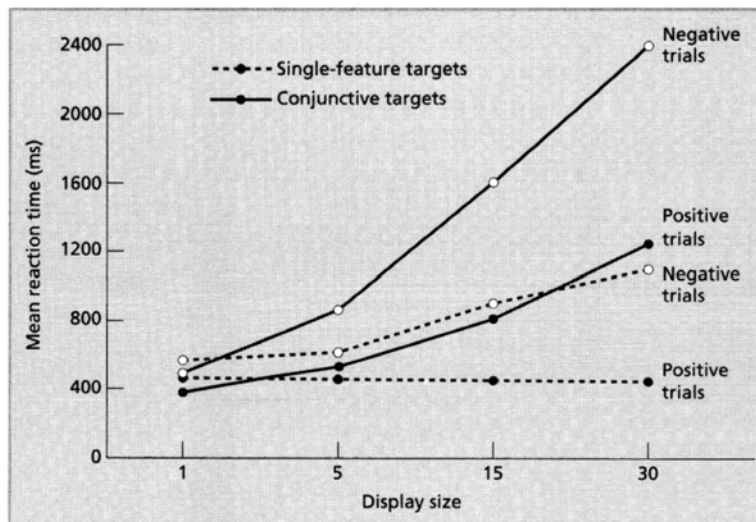
FIGURE 5.6

Performance speed on a detection task as a function of target definition (conjunctive vs. single feature) and display size. Adapted from Treisman and Gelade (1980).

• In the absence of focused attention or relevant stored knowledge, features from different objects will be combined randomly, producing "illusory conjunctions".

Treisman and Gelade (1980) had previously obtained support for this theory. Their participants searched for a target in a visual display having a set or display size of between 1 and 30 items. The target was either an object (a green letter T), or consisted of a single feature (a blue letter or an S). When the target was a green letter T, all the non-targets shared one feature with the target (i.e., they were either the brown letter T or the green letter X). The prediction was that focused attention would be needed to detect the object target (because it was defined by a combination of features), but would not be required to detect single-feature targets.

   The findings were as predicted (see Figure 5.6). Set or display size had a large effect on detection speed when the target was defined by a combination or conjunction of features (i.e., a green letter T), presumably because focused attention was required. However, there was very little effect of display size when the target was defined by a single feature (i.e., a blue letter or an S).

   According to feature integration theory, lack of focused attention can produce illusory conjunctions. Treisman and Schmidt (1982) confirmed this prediction. There were numerous illusory conjunctions when attention was widely distributed, but not when the stimuli were presented to focal attention. Balint's patients have problems with visual attention generally, especially with the accurate location of visual stimuli. Accordingly, it might be expected they would be liable to illusory conjunctions. Friedman-Hill, Robertson, and Treisman (1995) studied a Balint's patient. He made a remarkably large number of illusory conjunctions, miscombining the shape of one stimulus with the colour of another.

   Treisman and Sato (1990) developed feature integration theory. They argued that the degree of *similarity* between the target and the distractors influences visual search time. They found that visual search for an object target defined by more than one feature was typically limited to those distractors having at least one

of the target's features. For example, if you were looking for a blue circle in a display containing blue triangles, red circles, and red triangles, you would ignore red triangles. This contrasts with the views of Treisman and Gelade (1980), who argued that none of the stimuli would be ignored.

Treisman (1993) put forward a more complex version of feature integration theory, in which there are four kinds of attentional selection. First, there is selection by location involving a relatively broad or narrow attention window. Second, there is selection by features. Features are divided into surface-defining features (e.g., colour; brightness; relative motion) and shape-defining features (e.g., orientation; size). Third, there is selection on the basis of object-defined locations. Fourth, there is selection at a late stage of processing which determines the object file that controls the individual's response. Thus, attentional selectivity can operate at various levels depending on the particular demands of the current task.

Guided search theory

Guided search theory was put forward by Wolfe (1998). It represents a substantial refinement of feature integration theory. There is an overall similarity, in that it is assumed within guided search theory that visual search initially involves efficient feature-based processing, followed by less efficient search processes. However, Wolfe (1998) replaced Treisman and Gelade's (1980) assumption that the initial processing is necessarily parallel and subsequent processing is serial with the notion that processes are more or less efficient. He did so because of the diverse findings in the literature: "Results of visual search experiments run from flat to steep RT [reaction time]×set size functions with no evidence of a dichotomous division [division into two]…The continuum of search slopes does make it implausible to think that the search tasks, themselves, can be neatly classified as serial or parallel" (Wolfe, 1998, p. 20). Thus, there should be no effect of set or display size on detection times if parallel processing is used, but a substantial effect of set size if serial processing is used, but most actual findings fall between these two extremes.

According to guided search theory, the initial processing of basic features produces an activation map, in which each of the items in the visual display has its own level of activation. Suppose that someone is searching for red, horizontal targets. Feature processing would activate all red objects and all horizontal objects. Attention is then directed towards items on the basis of their level of activation, starting with those with the highest level of activation. This assumption allows us to understand why search times are longer when some of the non-targets share one or more features with the target stimuli (e.g., Duncan & Humphreys, 1989).

A great problem with the original version of feature integration theory is that targets in large displays are typically found faster than would be predicted. The activation-map notion provides a plausible way in which visual search can be made more efficient by ignoring stimuli not sharing any features with the target stimulus.

What are the basic features in visual search, and how can they be identified? According to Wolfe (1998, p. 23), the answer to the second question is as follows: "If a stimulus supports both efficient search *and* effortless segmentation [grouping], then it is probably safe to include it in the ranks of basic features." Wolfe (1998, p. 40) provided the following answer to the first question: "There appear to be about eight to ten basic features: colour, orientation, motion, size, curvature, depth, vernier offset [small irregularity in a line segment], gloss, and, perhaps, intersection."

Attentional engagement theory

Duncan and Humphreys (1989, 1992) put forward attentional engagement theory. This was designed in part to explain why visual search is often faster and more efficient than would be expected on the original version of feature integration theory. They made two key predictions:

- Search times will be slower when the similarity between the target and the non-targets is increased.
- Search times will be slower when there is reduced similarity among non-targets. Thus, the slowest search times are obtained when non-targets are dissimilar to each other, but similar to the target.

Evidence that visual search can be very rapid when non-targets are all the same was obtained by Humphreys, Riddoch, and Quinlan (1985). Participants detected inverted T targets against a background of Ts the right way up. Detection speed was hardly affected by the number of non-targets. According to feature integration theory, the fact that the target was defined by a combination or conjunction of features (i.e., a vertical line and a horizontal line) means that visual search should have been greatly affected by the number of non-targets.

   Duncan and Humpreys (1989, 1992) made the following theoretical assumptions:

- There is an initial parallel stage of perceptual segmentation and analysis based on all items.
- There is a later stage of processing in which selected information is entered into visual short-term memory; this corresponds to selective attention.
- The speed of visual search depends on how easily the target item enters visual short-term memory.
- Items well matched to the description of the target item are most likely to be selected for visual short-term memory; thus, non-targets that are similar to the target slow the search process.
- Items that are perceptually grouped (e.g., because they are very similar) will be selected (or rejected) together for visual short-term memory. Thus, dissimilar non-targets cannot be rejected together, and this slows the search process.

In the study by Treisman and Gelade (1980), there were long search times to detect a green letter T in a display containing brown Ts and green Xs (see Figure 5.6). Treisman and Gelade (1980) argued that this occurred because of the need for focal attention to produce the necessary conjunction of features. In contrast, Duncan and Humphreys (1989, 1992) claimed that the slow performance resulted from the high similarity between the target and non-target stimuli (the latter shared one of the features of the target stimulus) and the dissimilarity among the non-target stimuli (the two different non-targets shared no features).

   Humphreys and Müller (1993) produced a connectionist model based on attentional engagement theory. This model, known as SERR (SEarch via Recursive Rejection), was based on the assumption that grouping and search processes operate in a parallel fashion. Müller, Humphreys, and Donnelly (1994) compared the predictions of SERR against those of feature integration theory. The participants had to detect T-type targets as rapidly as possible, with the distractors consisting of Ts at various different orientations. In one condition, there were two or more identical targets, and the participants had to respond as soon as they detected one or them. The time taken to detect targets in this condition was faster than the fastest time taken to detect the target in another condition in which there was only a single target in the display. This finding follows from the SERR model with its emphasis on parallel processing, but is very hard for serial processing theories to explain.

Evaluation

   Feature integration theory has influenced theoretical approaches to visual search in various ways. First, it is generally agreed that two successive processes are involved. Second, it is accepted that the first process is fast and efficient, whereas the second process is slower and less efficient. Third, the notion that different visual features are processed independently or separately seems attractive in view of the evidence that

distinct areas of the visual cortex are specialised for processing different features (Zeki, 1993, see Chapter 2).

There were four key weaknesses with early versions of feature integration theory. First, as Wolfe (1998) pointed out, the assumption that visual search is either entirely parallel or serial is much too strong and disproved by the evidence. Second, the search for targets consisting of a conjunction or combination of features is faster than predicted by feature integration theory. Some of the factors involved are incorporated into guided search theory and attentional engagement theory. For example, search for conjunctive targets can be speeded up if non-targets can be grouped together or if non-targets share no features with targets.

Third, it was originally assumed within feature integration theory that the effect of set or display size on visual search depends mainly on the nature of the target (single feature or conjunctive feature). In fact, other factors (e.g., grouping of non-targets) also play a role.

Fourth, Treisman and Schmidt (1982) assumed that features are completely "free-floating" in the absence of focused attention. As a result, *any* features can combine together into illusory conjunctions. In fact, most illusory conjunctions occur between items that are close together rather than far apart (Ashby, Prinzmetal, Ivry, & Maddox, 1996). This led Ashby et al. (1996) to develop location uncertainty theory, according to which illusory conjunctions occur "because of uncertainty about the location of visual features" (p. 165).

Another issue with research on visual search concerns its relevance to the real world. As Wolfe (1998, p. 56) pointed out:

> In the real world, distractors are very heterogeneous [diverse]. Stimuli exist in many size scales in a single view. Items are probably defined by conjunctions of many features. You don't get several hundred trials with the same targets and distractors…A truly satisfying model of visual search will need …to account for the range of real-world visual behaviour.

Disorders of visual attention

Posner and Petersen (1990) proposed a theoretical framework within which various disorders of visual attention can be understood. They argued that three separate abilities are involved in controlling the attentional spotlight:

- *Disengagement* of attention from a given visual stimulus.
- *Shifting* of attention from one target stimulus to another.
- *Engaging* or locking attention on a new visual stimulus.

These three abilities are all functions of the posterior attention system. In addition, there is an anterior attention system. This is involved in co-ordinating the different aspects of visual attention, and resembles the central executive component of the working memory system (see Chapter 6). According to Posner and Petersen (1990, p. 10), there is "a hierarchy of attentional systems in which the anterior system can pass control to the posterior system when it is not occupied with processing other material."

Posner (1995) developed some of these ideas. The anterior attentional system based in the frontal lobes was regarded as controlling stimulus selection and the allocation of mental resources. The posterior attentional system is influenced by the anterior system and controls lower-level aspects of attention, such as the disengagement of attention. There is some evidence that the anterior attentional system may be more complex than was assumed by Posner (1995). For example, Stuss et al. (1999) found that damage to the left

frontal lobe produced a different pattern of disturbance of attention than did damage to the right frontal lobe. These findings suggest that there may be more than one anterior attentional system.

Disengagement of attention

Posner, Walker, Friedrich, and Rafal (1984) presented cues to the locations of forthcoming targets to neglect patients. The patients generally coped fairly well with this task, even when the cue and the target were both presented to the impaired visual field. However, when the cue was presented to the unimpaired visual field and the target was presented to the impaired visual field, the patients' performance was very poor. These findings suggest that the patients found it very hard to disengage their attention from visual stimuli presented to the unimpaired side of visual space. Thus, problems with disengagement play a significant role in producing the symptoms shown by neglect patients.

Patients with neglect have suffered damage to the parietal region of the brain (Posner et al., 1984). A different kind of evidence that the parietal area is important in attention was reported by Petersen, Corbetta, Miezin, and Shulman (1994). PET scans indicated that there was much activation within the parietal area when attention shifted from one spatial location to another.

Problems with disengaging attention are also found in Balint's syndrome patients suffering from simultanagnosia. In this condition (mentioned earlier), only one object (out of two or more) can be seen at any one time, even when the objects are close together. As most of these patients have full visual fields, it seems that the attended visual object exerts a "hold" on attention that makes disengagement difficult. However, neglected stimuli are processed to some extent. Coslett and Saffran (1991) observed strong effects of semantic relatedness between two briefly presented words in a patient with simultanagnosia.

Shifting of attention

Posner, Rafal, Choate, and Vaughan (1985) looked at problems of shifting attention by studying patients suffering from progressive supranuclear palsy. Such patients have damage to the midbrain, so they find it very hard to make voluntary eye movements, especially in the vertical direction. These patients responded to visual targets, and there were sometimes cues to the locations of forthcoming targets. There was a short, intermediate, or long interval between the cue and the target. At all intervals, valid cues (cues providing accurate information about target location) speeded up responding to the targets when the targets were presented to the left or the right of the cue. However, only cues at the long interval aided responding when the targets were presented above or below the cues. Thus, the patients had difficulty in shifting their attention in the vertical direction.

Attentional deficits apparently associated with shifting of attention have been studied in patients with Balint's syndrome. These patients have difficulty in reaching for stimuli using visual guidance. Humphreys and Riddoch (1993) presented two Balint's patients with 32 circles in a display. The circles were either all the same colour, or half were one colour and the other half a different colour. The circles were either close together or spaced, and the task was to decide whether they were all the same colour. On trials where there were circles of two colours, one of the patients (SA) performed much better when the circles were close together than when they were spaced (79% vs. 62%, respectively). The other patient (SP) performed equivalently in both conditions (62% vs. 59%, respectively). Apparently some patients with Balint's syndrome (e.g., SA) find it hard to shift attention within the visual field.

Engaging attention

Rafal and Posner (1987) studied problems of engaging attention in patients with damage to the pulvinar nucleus of the thalamus. These patients were given the task of responding to visual targets that were

preceded by cues. The patients responded faster when the cues were valid than when they were invalid, regardless of whether the target stimulus was presented to the same side as the brain damage or to the opposite side. However, they responded rather slowly following both kinds of cues when the target stimulus was presented to the side of the visual field opposite to that of the brain damage. According to Rafal and Posner (1987), these findings reflect a problem the patients have in engaging attention to such stimuli.

Additional evidence that the pulvinar nucleus of the thalamus is involved in controlling focused attention was obtained by LaBerge and Buchsbaum (1990). PET scans indicated increased activation in the pulvinar nucleus when participants were told to ignore a given stimulus. Thus, the pulvinar nucleus is involved in preventing attention from being focused on an unwanted stimulus as well as in directing attention to significant stimuli.

Section summary

As Posner and Petersen (1990, p. 28) pointed out, the findings indicate that "the parietal lobe first disengages attention from its present focus, then the midbrain area acts to move the index of attention to the area of the target, and the pulvinar nucleus is involved in reading out data from the indexed locations". An important implication is that the attentional system is rather complex. As Allport (1989, p. 644) expressed it, "spatial attention is a distributed function in which many functionally differentiated structures participate, rather than a function controlled uniquely by a single centre". This increased understanding of the complexities of attention has arisen in large part because of the study of brain-damaged patients.

DIVIDED ATTENTION

What happens when people try to do two things at once? The answer clearly depends on the nature of the two "things". Sometimes the attempt is successful, as when an experienced motorist drives a car and holds a conversation at the same time, or a tennis player notes the position of his or her opponent while running at speed and preparing to make a stroke. At other times, as when someone tries to rub their stomach with one hand while patting their head with the other, there can be a complete disruption of performance.

Hampson (1989) made the key point that focused and divided attention are more similar than might have been expected. Factors such as use of different modalities which aid focused or selective attention generally also make divided attention easier. According to Hampson (1989, p. 267), "anything which minimises interference between processes, or keeps them 'further apart' will allow them to be dealt with more readily either selectively or together."

Theoretically, breakdowns of performance when two tasks are combined shed light on the limitations of the human information-processing system. Some theorists (e.g., Norman & Shallice, 1986) argue that such breakdowns reflect the limited capacity of a single multi-purpose central processor or executive sometimes described as "attention". Other theorists are more impressed by our apparent ability to perform two fairly complex tasks at the same time without disruption or interference. Such theorists favour the notion of several specific processing resources, arguing that there will be no interference between two tasks provided that they make use of different processing resources.

More progress has been made empirically than theoretically. It is possible to predict fairly accurately whether or not two tasks can be combined successfully, but the accounts offered by different theorists are very diverse. Accordingly, we will discuss some of the factual evidence before moving on to the murkier issue of how the data are to be explained.

Factors determining dual-task performance

Task similarity

When we think of pairs of activities that are performed well together in everyday life, the examples that come to mind usually involve two rather dissimilar activities (e.g., driving and talking; reading and listening to music). As we have seen, when people shadow or repeat back prose passages while learning auditorily presented words, their subsequent recognition-memory performance for the words is at chance level (Allport et al., 1972). However, the same authors found that memory was excellent when the to-be-remembered material consisted of pictures.

Various kinds of similarity need to be distinguished. Wickens (1984) reviewed the evidence and concluded that two tasks interfere to the extent that they have the same stimulus modality (e.g., visual or auditory), make use of the same stages of processing (input, internal processing, and output), and rely on related memory codes (e.g., verbal or visual). Response similarity is also important. McLeod (1977) asked participants to perform a continuous tracking task with manual responding together with a tone-identification task. Some participants responded vocally to the tones, whereas others responded with the hand not involved in the tracking task. Performance on the tracking task was worse with high response similarity (manual responses on both tasks) than with low response similarity (manual responses on one task and vocal ones on the other).

Similarity of stimulus modality has probably been studied most thoroughly. Treisman and Davies (1973) found two monitoring tasks interfered with each much more when the stimuli on both tasks were in the same sense modality (visual or auditory) than when they were in different modalities.

It is often very hard to measure similarity. How similar are piano playing and poetry writing, or driving a car and watching a football match? Only when there is a better understanding of the processes involved in the performance of such tasks will sensible answers be forthcoming.

Practice

Common sense suggests that the old saying "Practice makes perfect" is especially applicable to dual-task performance. For example, learner drivers find it almost impossible to drive and hold a conversation, whereas expert drivers find it fairly easy. Support for this commonsensical position was obtained by Spelke, Hirst, and Neisser (1976) in a study on two students called Diane and John. These students received five hours' training a week for four months on a variety of tasks. Their first task was to read short stories for comprehension while writing down words to dictation. They found this very hard initially, and their reading speed and handwriting both suffered considerably. After six weeks of training, however, they could read as rapidly and with as much comprehension when taking dictation as when only reading, and the quality of their handwriting had also improved.

In spite of this impressive dual-task performance, Spelke et al. were still not satisfied. Diane and John could recall only 35 out of the thousands of words they had written down at dictation. Even when 20 successive dictated words formed a sentence or came from a single semantic category, the two students were unaware of that. With further training, however, they learned to write down the names of the categories to which the dictated words belonged while maintaining normal reading speed and comprehension.

Spelke et al. (1976, p. 229) wondered whether the popular notion that we have limited processing capacity is accurate, basing themselves on the dramatic findings with John and Diane: "People's ability to develop skills in specialised situations is so great that it may never be possible to define general limits on cognitive capacity." However, there are alternative ways of interpreting their findings. Perhaps the dictation

task was performed rather automatically, and so placed few demands on cognitive capacity, or there might have been a rapid alternation of attention between reading and writing. Hirst et al. (1980) claimed that writing to dictation was not done automatically, because the students understood what they were writing. They also claimed that reading and dictation could only be performed together with success by alternation of attention if the reading material were simple and highly redundant. However, they found that most participants could still read and take dictation effectively when less redundant reading matter was used.

Do the studies by Spelke et al. (1976) and by Hirst et al. (1980) show that two complex tasks can be performed together without disruption? One of the participants used by Hirst et al. was tested at dictation *without* reading, and made fewer than half the number of errors that occurred when reading at the same time. Furthermore, the reading task gave the participants much flexibility in terms of when they attended to the reading matter, and such flexibility means that there may well have been some alternation of attention between tasks.

There are other cases of apparently successful performance of two complex tasks, but the requisite skills were always highly practised. Expert pianists can play from seen music while repeating back or shadowing heard speech (Allport et al., 1972), and an expert typist can type and shadow at the same time (Shaffer, 1975). These studies are often regarded as providing evidence of completely successful task combination. However, there are signs of interference when the data are inspected closely (Broadbent, 1982).

Why might practice aid dual-task performance? First, participants may develop new strategies for performing the tasks to minimise task interference. Second, the demands that a task makes on attentional or other central resources may be reduced with practice. Third, although a task initially requires the use of several specific processing resources, practice may reduce the number of resources required. These possibilities are considered in more detail later.

Task difficulty

The ability to perform two tasks together depends on their difficulty, and there are several studies showing the expected pattern of results. For example Sullivan (1976) used the tasks of shadowing an auditory message and detecting target words on a non-shadowed message at the same time. When the shadowing task was made harder by using a less redundant message, fewer targets were detected on the non-shadowed message. However, it is hard to define "task difficulty" with any precision.

The demands for resources of two tasks performed together might be thought to equal the sums of the demands of the two tasks when performed separately. However, the necessity to perform two tasks together often introduces new demands of co-ordination and avoidance of interference. Duncan (1979) asked his participants to respond to closely successive stimuli, one requiring a left-hand response and the other a right-hand response. The relationship between each stimulus and response was either corresponding (e.g., rightmost stimulus calling for response of the rightmost finger) or crossed (e.g., leftmost stimulus calling for response of the rightmost finger). Performance was poor when the relationship was corresponding for one stimulus but crossed for the other. In these circumstances, the participants were sometimes confused, with their errors being largely those expected if the inappropriate stimulus-response relationship had been selected.

Bottleneck theories

Welford (1952) argued that there is a bottleneck in the processing system making it hard (or impossible) for two decisions about the appropriate responses to two different stimuli to be made at the same time. Much of the supporting evidence comes from studies of the *psychological refractory period*. In these studies, there
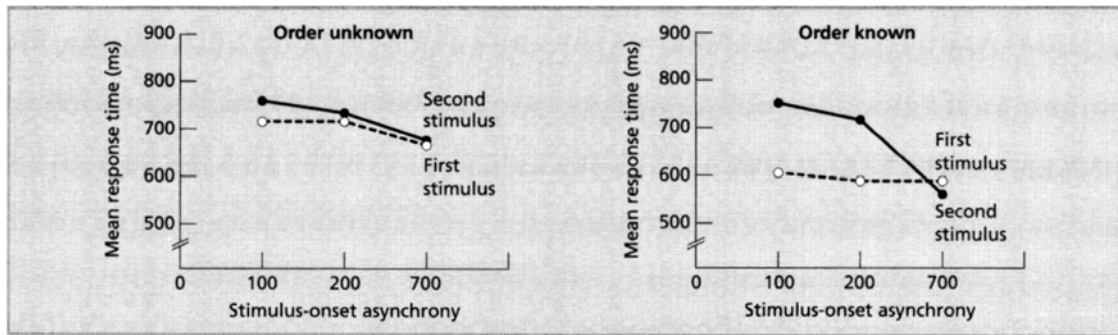
FIGURE 5.7

Response times to the first and second stimuli as a function of time between the onset of the stimuli (stimulus-onset asynchrony) and whether or not the order of the stimuli was known beforehand. Adapted from Pashler (1990).

are two stimuli (e g., two lights) and two responses (e.g., button presses), and the task is to respond to each stimulus as rapidly as possible. When the second stimulus is presented very shortly after the first one, there is generally a marked slowing of the response to the second stimulus: this is known as the psychological refractory period effect (see Welford, 1952).

It could be argued that the psychological refractory period occurs simply because people are not used to responding to two immediately successive stimuli. However, Pashler (1993) discussed one of his studies in which the effect was still observable after more than 10,000 practice trials.

Another objection to the notion that the delay in responding to the second stimulus reflects a bottleneck in processing is that the effect is due to similarity of stimuli and/or similarity of responses. According to the bottleneck theory, the psychological refractory period effect should be present even when the two stimuli and responses differ greatly. In contrast, the effect should disappear if similarity is crucial. Pashler (1990) used a tone requiring a vocal response and a visual letter requiring a button-push response. Some participants were told the order in which the stimuli would be presented, whereas the others were not. In spite of a lack of either stimulus or response similarity, there was a psychological refractory period effect, and it was greater when the order of stimuli was known than when it was not (see Figure 5.7). Thus, the findings provided strong support for the bottleneck position.

Pashler (1998, p. 177) ended his review with the following conclusion:

> If there were no fundamental constraint preventing central stages of multiple tasks from being carried out simultaneously, one might expect that exceptions to PRP [psychological refractory period] interference would be encountered frequently But in fact,… only a handful of exceptions have been noted …These exceptions have generally been interpreted as indicating that certain specific neural pathways are capable of bypassing the central bottleneck.

Earlier we discussed studies (e.g., Hirst et al., 1980; Spelke et al., 1976) in which two complex tasks were performed remarkably well together. Such findings make it hard to argue for the existence of a bottleneck in processing. However, studies on the psychological refractory period have the advantage of very precise assessment of the time taken to respond to any given stimulus. The coarse-grained measures obtained in studies such as those of Spelke et al. (1976) and Hirst et al. (1980) may simply be too insensitive to permit detection of bottlenecks.

It has been assumed so far that there is a single bottleneck, but there may be multiple bottlenecks. Pashler (1998, p. 175) addressed this issue: "At present,…a single bottleneck seems sufficient to account for the response delays observed in 'standard' PRP designs involving pairs of choice RT [response time] tasks. In fact, results from these paradigms are difficult to square with the existence of multiple bottlenecks."

Pashler et al. (1994) studied *split-brain patients,* in whom the connections between the cortical hemispheres have been surgically cut. One stimulus-response task was presented to one hemisphere and the other was presented to the other hemisphere. If the bottleneck is located in the cortex, then it might be expected that these patients would not show the psychological refractory period effect. In fact, they had a normal effect, suggesting that sub-cortical structures underlie the effect.

The evidence from studies of the psychological refractory period indicates that there is a bottleneck, and that some processing is serial. However, the size of the psychological refractory period is typically not very large, and suggests that most processes do not operate in a serial way. As Pashler (1998, p. 184) pointed out, "The idea of obligatory serial central processing is quite consistent with a great deal of parallel processing."

Central capacity theories

A simple way of accounting for many dual-task findings is to assume there is some central capacity (e.g. central executive) which can be used flexibly across a wide range of activities. This central processor has strictly limited resources, and is sometimes known as attention or effort. The extent to which two tasks can be performed together depends on the demands that each task makes on those resources. If the combined demands of the two tasks do not exceed the total resources of the central capacity, then the two tasks will not interfere with each other. However, if the resources are insufficient, then performance disruption is inevitable.

One of the best known of the capacity theories was put forward by Kahneman (1973). He argued that attentional capacity is limited but the capacity can vary somewhat. More specifically, it is greater when task difficulty is high than when it is low, and it increases in conditions of high effort or motivation. Increased effort tends to produce physiological arousal, and this can be assessed in various ways (e.g., pupillary dilation).

There are various problems with Kahneman's (1973) theory. He did not define his key terms very clearly, referring to a "a nonspecific input, which may be variously labelled 'effort', 'capacity', or 'attention'." Another problem is that it is assumed that effort and attentional capacity are determined in part by task difficulty, but it is very hard to determine the difficulty of a task with any precision.

Bourke, Duncan, and Nimmo-Smith (1996) tested predictions of central capacity theory. They selected four tasks that were designed to be as different as possible:

1. Random generation: generating letters at random.
2. Prototype learning: working out the features of two patterns or prototypes from seeing various exemplars.
3. Manual task: screwing a nut down to the bottom of a bolt and back up to the top, and then down to the bottom of a second bolt and back up, and so on.
4. Tone task: detecting the occurrence of a target tone.

The participants were given two of these tasks to perform together, with one task being identified as more important than the other. The basic argument was as follows: if there is a central or general capacity, then

the task making most demands on this capacity will interfere most with all three of the other tasks. In contrast, the task making fewest demands on this capacity will intefere least with all the other tasks.

What did Bourke et al. (1996) find? First, these very different tasks did interfere with each other. Second, the random generation task interfered the most overall with the performance of the other tasks, and the tone
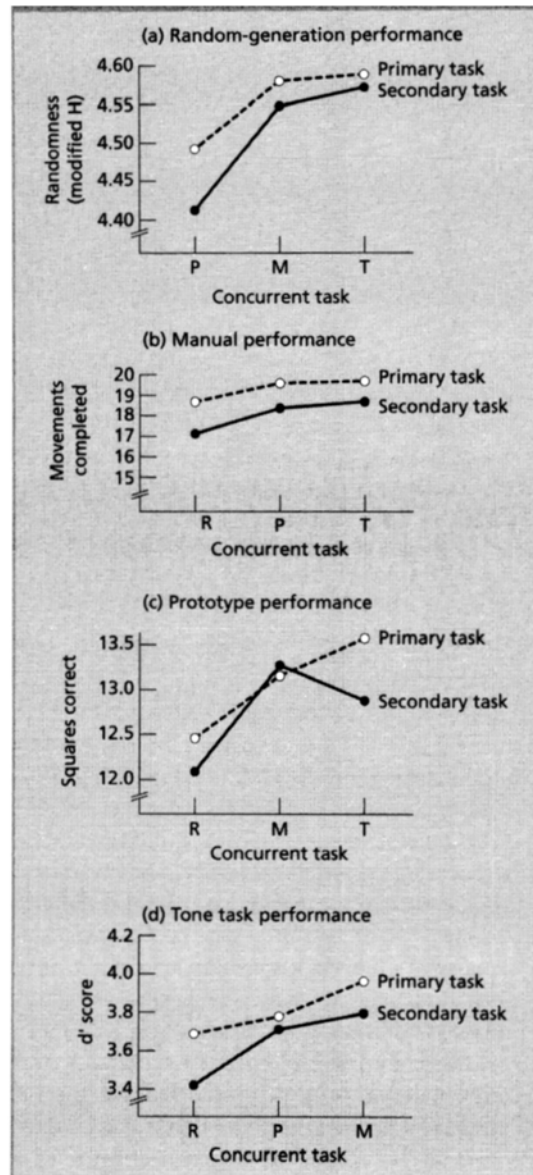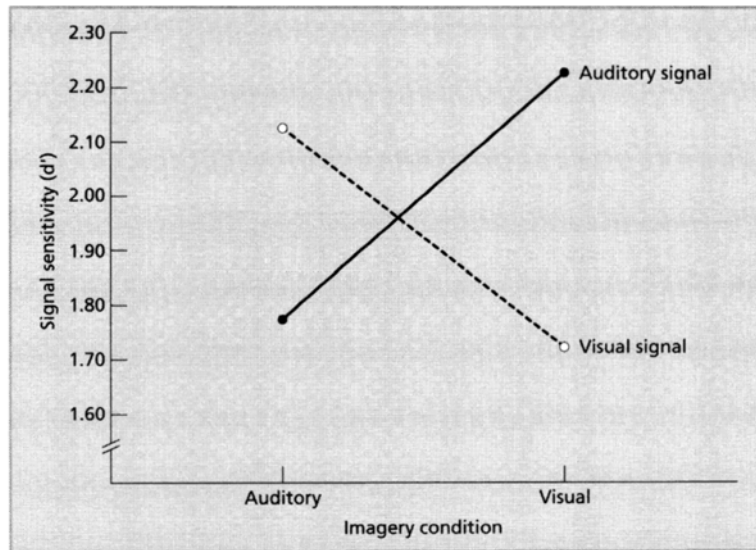
FIGURE 5.8

Performance on random generation (R), prototype learning (P), manual (M), and tone (T) tasks as a function of concurrent task. Adapted from Bourke et al. (1996).

task interfered the least. Third, and of greatest importance, the random generation task consistently interfered most with the prototype, manual, and tone tasks, and it did so whether it was the primary or the secondary task (see Figure 5.8). The tone task consistently interfered least with each of the other three tasks. Thus, the findings accorded with the predictions of a general capacity theory.

FIGURE 5.9

Sensitivity (d') to auditory and visual signals as a function of concurrent imagery modality (auditory vs. visual). Adapted from Segal and Fusella (1970).

The main limitation of the study by Bourke et al. (1996) is that it did not clarify the nature of the central capacity. As they admitted (1996, p. 544).

> The general factor may be a limited pool of processing resource that needs to be invested for a task to be performed. It may be a limited central executive that coordinates or monitors other processes and is limited in how much it can deal with at one time. It may also represent a general limit of the entire cognitive system on the amount of information that can be processed at a given time. The method developed here deals only with the existence of a general factor in dual-task decrements, not its nature.

Evaluation

Central capacity theories cannot explain all the findings. According to such theories, the crucial determinant of dual-task performance is the difficulty level of the two tasks, with difficulty being defined in terms of the demands placed on the resoures of the central capacity. However, the effects of task difficulty are often swamped by those of task similarity. For example, Segal and Fusella (1970) combined image construction (visual or auditory) with signal detection (visual or auditory). The auditory image task impaired detection of auditory signals more than did the visual task (see Figure 5.9), suggesting that the auditory image task was more demanding than the visual image task. However, the auditory image task was less disruptive than the visual image task when each task was combined with a task requiring detection of visual signals, suggesting the opposite conclusion. In this study, task similarity was clearly a much more important factor than task difficulty.

Allport (1989, p. 647) argued that such findings, "point to a multiplicity of attentional functions, dependent on a multiplicity of specialised subsystems. No one of these subsystems appears uniquely

'central'." It is possible to "explain" dual-task performance by assuming that the resources of some central capacity have been exceeded, and to account for a lack of interference by assuming that the two tasks did not exceed those resources. However, in the absence of any independent assessment of central processing capacity, this is simply a re-description of the findings rather than an explanation.

Modular theories

The views of central capacity theorists can be compared with those of cognitive neuropsychologists, who assume that the processing system is modular (i.e., consisting of numerous fairly independent processors or modules). Evidence for modularity comes from the study of language in brain-damaged patients (see Chapters 12 and 13). If the processing system consists of specific processing mechanisms, then it is clear why the degree of similarity between two tasks is so important: similar tasks compete for the same specific processing mechanisms or modules, and thus produce interference, whereas dissimilar tasks involve different modules, and so do not interfere.

   Allport (1989) and others have argued that dual-task performance can be accounted for in terms of modules or specific processing resources. However, there are significant problems with this theoretical approach. First, it does not provide an adequate explanation of findings on the psychological refractory period effect. Second, there is no consensus regarding the nature or number of these processing modules. Third, most modular theories cannot be falsified. Whatever the findings, it is always possible to account for them by assuming the existence of appropriate specific modules. Fourth, if there were several modules operating in parallel, there would be substantial problems in terms of co-ordinating their outputs to produce coherent behaviour

Synthesis theories

Some theorists (e.g., Baddeley, 1986; Eysenck, 1982) favour an approach based on a synthesis of the central capacity and modular notions. According to them, there is a hierarchical structure. The central processor or central executive is at the top of the hierarchy, and is involved in the co-ordination and control of behaviour. Below this level are specific processing mechanisms operating relatively independently of each other.

   One of the problems with the notion that there are several specific processing mechanisms and one general processing mechanism is that there does not appear to be a unitary attentional system. As we saw in the earlier discussion of cognitive neuropsychological findings, it seems that somewhat separate mechanisms are involved in disengaging, shifting, and engaging attention. If there is no general processing mechanism, then it may be unrealistic to assume that the processing system possesses a hierarchical structure.

AUTOMATIC PROCESSING

A key phenomenon in studies of divided attention is the dramatic improvement that practice often has on performance. The commonest explanation for this phenomenon is that some processing activities become automatic as a result of prolonged practice. There is reasonable agreement on the criteria for automatic processes:

• They are fast.
• They do not reduce the capacity for performing other tasks (i.e., they demand zero attention).